A Fluid Mud Transport Model in Multi-dimensions

Tian-Jian Hsu
Civil and Coastal Engineering, University of Florida, Gainesville, FL 32608
phone: (352) 392-9537 fax:(352) 392-3394 email: thsu@ufl.edu

Peter A. Traykovski
Woods Hole Oceanographic Institution, MS#11, Woods Hole, MA 02543

Award Number: N00014-07-1-0494

LONG-TERM GOALS

The long term goal is to develop a robust multi-phase, multi-class numerical modeling framework for both cohesive and non-cohesive sediment transport in the fluvial and coastal environments.

OBJECTIVES

The objectives of the present study focus on extending a fluid mud model for boundary-layer-driven and gravity-driven transport (Hsu et al. 2007) with several new capabilities. Specifically, the objectives are to:

- Conduct comprehensive model-data comparisons with laboratory/field observed fluid mud processes, specifically in conjunction with new MURI initiative for understanding wave-mud interaction.

- In conjunction to NOPP-Community Sediment Transport Model initiative, the fluid model is utilized to provide parameterizations for wave-boundary-layer-scale transport processes.

- Extend the existing fluid mud model with a bed module to enable direct modeling on consolidation/fluidization. Extend the model to multi-dimensional for various coastal and estuarine applications.

APPROACH

It is important to understand the fate of terrestrial sediment into the coastal ocean, because it determines for example the seabed properties and the turbidity of the water column. Several recent initiatives, such as *NOPP Community Sediment Transport Model*, *MURI- Understading Wave-Mud Interaction* and *Tidal Mud Flats DRI* have put forward new outstanding science and technical questions for coastal sediment. The success of these new studies inevitably depends on our level of understandings on the crucial small-scale mechanisms that can be either resolved or parameterized via detailed measurement and modeling. These new initiatives also have a similar goal to establish improved understanding on coastal hydrodynamics and sediment transport processes in heterogeneous environment with more emphasis on cohesive sediment transport.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **A Fluid Mud Transport Model in Multi-dimensions**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Florida,Civil and Coastal Engineering,Gainesville,FL,32608**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

The dynamics of fluid-mud transport involve a variety of physical mechanisms, including for example, the boundary layer and gravity-driven transport, turbulence modulation, flocculation, non-Newtonian rheological behavior and consolidation (Dyer 1989; Mehta 1989). Hence, a general modeling framework for fluid mud need to be based on multiphase flow theory. In this study, a fluid mud model based on Fast Equilibrium Eulerian Approximation (Ferry and Balachandar 2001) to the multiphase equations appropriate for fine sediment has been developed and extended to model various cohesive sediment transport processes. An earlier version of this fluid mud model (Hsu et al. 2007) has been shown to be capable of modeling tidal-driven fluid mud (Kineke et al. 1996) and wave-supported gravity-driven mudflows (Traykovski et al. 2007).

WORK COMPLETED

Further development of the fluid mud model and understanding of various cohesive sediment transport processes are carried out in several directions:

Extend to 2D and incorporate Bingham rheology: The previous 1DV fluid mud modeling framework (Hsu et al. 2007), is extended to 2D to simulate wave-mud interaction. A 2D numerical wave model (COBRAS, Lin & Liu 1998) based on Reynolds-averaged Navier-Stokes (RANS) equations with Volume of Fluid (VOF) method for free-surface tracking is modified to solve the proposed fluid mud equations. Notice that the proposed governing equations for fluid mud and the related closures reduce to single-phase RANS equation when mud concentration becomes zero. Hence, the numerical model calculates wave propagation, sediment-laden wave boundary layer, fluid mud transport and their interactions continuously and consistently with one single set of balance equations and closures (i.e., no matching is required at mud-water interface). Currently, we calculate the rheological stress based on a mathematical form that is similar to Bingham rheology (Le Hir et al. 2001; Mei and Liu 1987; Frigaard and Nouar 2005). Essentially, a sediment viscosity is utilized which is depending on local strain rate and fluid mud concentration. Model results for cnoidal wave propagating over a 190 meter muddy seabed are shown in figure 1.

Parameterization of wave-supported gravity-driven mudflows: Typical coastal models, such as the ongoing NOPP-Community Sediment Transport Model (NOPP-CSTM) are not designed to resolve the thin wave boundary layer near the seabed. Hence, processes that occur within the wave boundary layer need to be parameterized as sub-module to provide quantities such as bottom drag coefficient and sediment transport rate. The fluid mud model is utilized to study fluid mud transport in the wave-current boundary layer. Specifically, model results are used to provide parameterizations for wave-supported gravity-driven mudflows (Traykovski et al. 2007). The nature and the existence of wave-supported gravity-driven mudflows are diagnosed by varying the floc properties, bed erodibility and rheological stresses. By selecting representative downslope fluid mud transport events, numerical experiments are conducted to study the effect of wave and long-shelf current intensities on the fluid mud transport, and its parameterization (Wright et al. 2001). Model results suggest that the drag coefficient decreases with increasing wave intensity, and seems to follow a power law. The bulk Richardson numbers is less sensitive to wave intensity but has a magnitude about 0.08, which is factor 3 smaller than the critical Richardson number. The dependence of wave-supported gravity-driven mudflows on long-shelf current intensity is also less sensitive compared to that on wave intensity. However, when the long-shelf current is as large as about 1.0 m/s at 1 m above the bed, auto-suspension may occur.

Flocculation: A balance equation for floc diameter in response to floc aggregation and break-up process in turbulent flow (Winterwerp 1998) is incorporated in the 1DV fluid mud model. The numerical model is able to calculate the spatial and temporal variation of floc size in turbulent boundary layer (with turbulence quantities provided by the k-ε closure) using a fixed fractal dimension. Notice that fractal dimension is required to specify the excess density of the mud floc (and hence the settling velocity). Based on field/laboratory observations, the fractal dimension is not a constant and shall change dynamically with the carrier turbulent flow (e.g., Dyer and Manning 1999). Recently, Khelifa and Hill (2006) proposed a model for settling velocity that utilizes a variable fractal dimension depending on the floc size itself (e.g., fractal dimension becomes 3.0 when floc size reduces to that of primary particle). They demonstrate that variable fractal dimension is more appropriate to relate measured floc size with settling velocity in the field and laboratory. In this study, we further derive the balance equations for floc dynamics based on the variable fractal dimension and come up a new model for floc dynamics that is able to be coupled with numerical model for fluid mud transport. The new formulation is shown to predict the equilibrium floc size under different turbulent shear rates measured in the laboratory (Son and Hsu, submitted).

Development of a unified transport/consolidation/fluidization model: Traditionally the geotechnical engineering community has been interested in the consolidation processes using for example Gibson's equation (Gibson et al. 1967). However, in order to predict morphological evolution in a dynamic muddy environment, both the consolidation and fluidization/liquefaction under turbulent shear flow have to be modeled. Hence, there is a need to come up with a more general modeling framework for mud bed dynamics. In terms of the governing equation, existing simplified multiphase flow theory can be directly adopted (see Toorman 1999 for a similar approach). The difficulties are the appropriate closures for rheology, effective stress and permeability. A series of work by Kranenburg (1994) and Merckelbach and Kranenburg (2004) suggested that if we assume floc is self-similar on all scales, specific relations exist between the fractal dimension and various properties of the cohesive sediment, such as the rheology, effective stress and permeability. Applying such theory to existing consolidation test data Kranenburg (1994) found that fractal dimension is around 2.75, which is much larger than that of typical floc aggregates in mobile suspension. This suggests that a complete consolidation/fluidization formulation shall incorporate floc dynamics with variable fractal dimension. We are currently working on the theoretical formulation of this process. In the future, such formulation can be directly adopted in the fluid mud model.

RESULTS

The fluid mud modeling framework is implemented into a numerical wave model COBRAS to directly simulate wave-mud interaction. Here, we describe a simple example to demonstrate the model capability. A Cnoidal wave train of wave height 0.72m, wave period 6 sec is sent into the numerical wave tank of water depth 2.5 m and total length 200 m (see Fig 1). Between x=10 m and 190 m, fluid mud of floc size d=22 mμ and specific gravity s=1.34 is allowed to be suspended by waves. A snapshot of the model results at t=72 sec is shown in Fig 1a for the entire numerical wave tank and Fig 1b for a close-up view near the bed. A thick layer of fluid mud is suspended with a thickness of about 50 cm. Fine grid of Δz=2mm in the vertical direction is implemented and hence the wave boundary layer structure and lutocline are resolved. The grid size in the horizontal direction is Δx=20cm, which is appropriate to resolve the Reynolds-averaged wave field. The dashed curve near the free-surface in Fig 1a represents the free-surface elevation from another independent computation without the fluid mud (i.e., clear fluid case) at the same instant. Apparently, the wave height starts to decay as the wave train propagates further downstream over the muddy bottom. Fig 1c presents model result of time history of free-surface elevation at wave guage *x*=190 m (solid curve). This result can be compared with guage data obtained at *x*=10m (right before the waves propagate into the mud regime, light-dotted curve) or obtained at the same location (*x*=190 m) but due to another independent computation without the presence of mud. We observed that the wave height is damped by about 18% due to propagation over muddy bottom of 180 m in length.

More insights can be revealed when examining the near-bed wave boundary layer structure (see Fig 1b). Without the fluid mud, the thickness of the wave boundary layer is only about 2cm (e.g., see dashed curve at *x*=23 m), which is about 10 time smaller than that with the fluid mud (about 20cm, see solid curve at *x*=23m). Due to the presence of fluid mud, large rheological shear stress provides an additional mechanism to mix the flow momentum across the wave boundary layer (in additional to turbulent shear stress) and hence the resulting wave boundary layer is much thicker. This enhanced wave boundary layer further allows suspension of a thicker layer of fluid mud (note that the thickness of fluid mud layer often scales with wave boundary layer thickness). The damping of the wave amplitude is apparently caused by (1) direct energy dissipation through rheological stress term in the momentum equation; (2) indirect mechanism due to greatly enhanced wave boundary layer thickness (and hence turbulence in the wave boundary layer). In summery, the damping of wave due to fluid mud is rather interactive. The thicknesses of the wave boundary layer and fluid mud layer are inter-dependent and it is difficult to prescribe it as a priori.

More comprehensive simulations using various wave conditions, mud properties, rheological closures shall be conducted in year 2. Currently, the computation is limited by CPU-time. In year 2, a postdoc researcher, Dr. Torres-Freyermuth, who use to develop a more efficient version of COBRAS (Dr. Losada’s group in Universidad de Cantabria, Spain) based on Fortran90 with C++ library will be joining UF and work on the 2D fluid mud model for wave-mud interaction. In year 2, we will also start working model-data comparison on measured wave boundary layer and fluid mud data by co-PI Traykovski at Atchafalaya shelf using both 1DV and 2D models.

IMPACT/APPLICATIONS

The present research efforts focus on developing a detailed numerical modeling framework for cohesive sediment transport. Currently, the PIs are also actively participating in other related initiatives. It is expected that by the end of this 2-year project, a numerical tool will be made available to the research community for small-scale cohesive sediment transport processes. The PIs are also partners of the ongoing NOPP-CSTM. In this collaborative modeling project, we utilize the small-scale model to study wave-supported gravity-driven fluid mud and provide parameterizations for large-scale coastal modeling system.

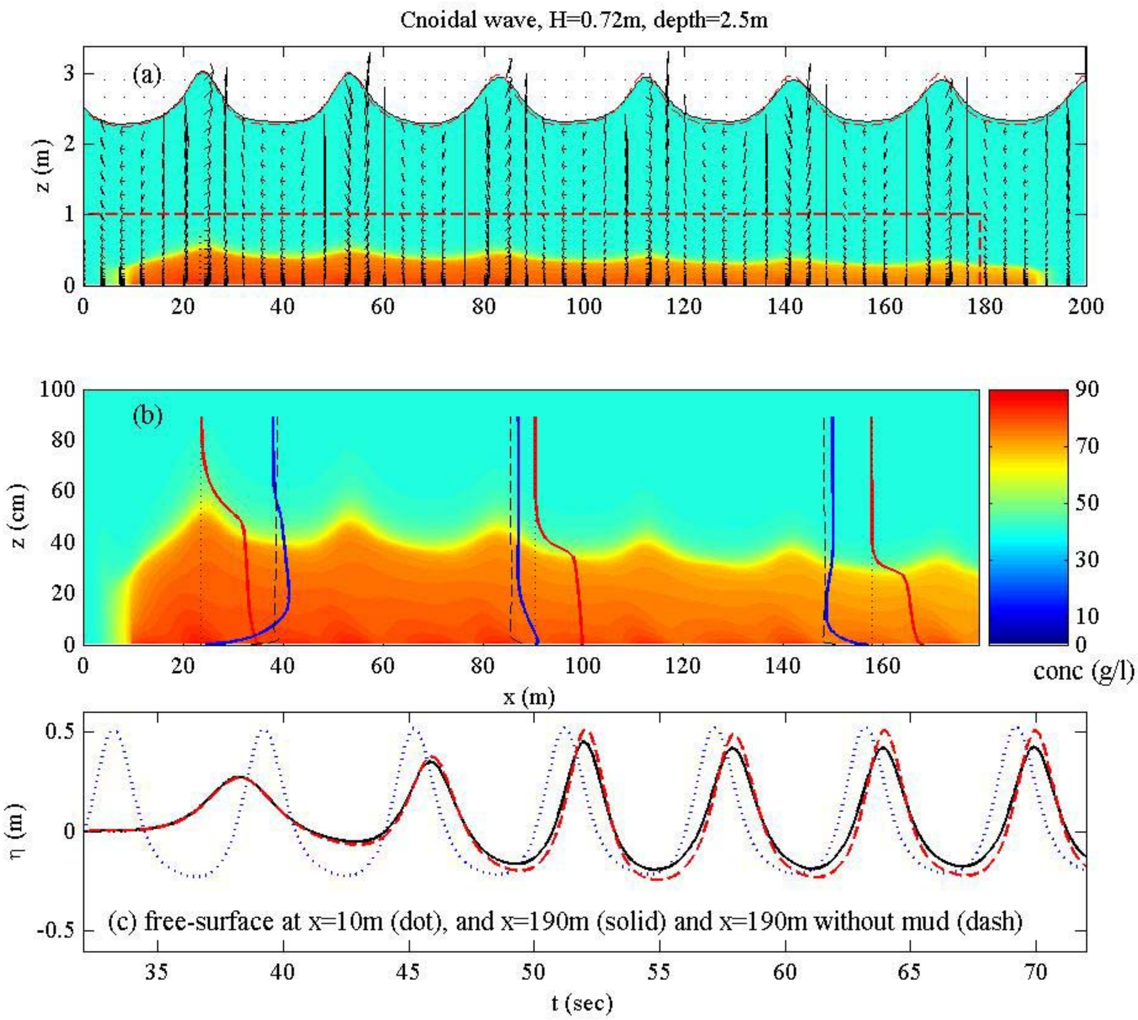

Figure 1: (a) Snapshot of the model results for free-surface elevation, wave velocity field and mud concentration in the numerical wave tank. The dashed curve near the free-surface is the corresponding free-surface elevation without fluid mud. (b) Enlarge view near the bed with mud concentration, wave boundary layer velocity at three locations. The dashed curves are corresponding velocity profiles without the presence of mud. (c) Comparison of wave guage data at x=190 m. Dashed curve represents model results without mud. The light dotted curve is guage results at x=10m (before propagating into the mud regime). At this instant (t=72 sec), the wave height is damped by 18% due to propagating over fluid mud regime of 180 m in length.

REFERENCES

Dyer, K. R., 1989, Sediment processes in estuaries: future research requirements, *J. Geophy. Res.*, 94(C10), 14327-14339.

Dyer, K.R. and Manning, A.J. 1999. Observation of the Size, Settling Velocity and Effective Density of Flocs, and Their Fractal Dimensions. *J. Sea Res*. 41, 87-95.

Ferry, J. and Balachandar, S., 2001, A fast Eulerian method for disperse two-phase flow, Int. J. Multiphase Flow, (27), 1199-1226.

Frigaard, I. A., and Nouar, C., 2005. On the usage of viscosity regularization methods for visco-plastic fluid flow computation, *J. Non-Newtonian Fluid Mech*, 127, 1-26.

Gibson RE, Englund GL, Hussey MJL. 1967, The theory of one-dimensional consolidation of saturated clays. I. Finite non-linear consolidation of thin homogeneous layers. *Geotechnique*, 17(3), 261-273.

Hsu, T-J, Traykovski P. A., and Kineke, G. C., 2007. On modeling boundary layer and gravity driven fluid mud transport, *J. Geophys. Res.*, 112, C04011, doi:10.1029/2006JC003719.

Khelifa, A. and Hill, P.S., 2006. Models for Effective Density and Settling Velocity of Flocs. *J. Hydraul. Res*. 44(3), 390-401.

Kranenburg, C. 1994. The Fractal Structure of Cohesive Sediment Aggregates. *Estuarine Coastal Shelf Sci*. 39, 451-460.

Kineke, G. C., R. W. Sternberg, J. H. Trowbridge, and W. R. Geyer, 1996, Fluid-mud processes on the Amazon continental shelf, *Cont. Shelf Res.*, 16(5/6), 667– 696.

Lin, P. and Liu, P. L.-F., 1998. A numerical study of breaking waves in the surf zone. *J. Fluid Mech*., Vol. 359, 239-264.

Li Hir, P., Bassoulet, P., Jestin, H., (2001), Application of the continuous modeling concept to simulate high-concentration suspended sediment in a macro-tidal estuary, in *Coastal and Estuarine Fine Sediment Processes*, ed. W. H. McAnally and A. J. Metha, Elsevier Proceedings in Marine Science, 229-248.

Mehta, A. J., 1989, On estuarine cohesive sediment suspension behavior, *J. Geophy. Res.*, 94(C10), 14303-14313.

Mei, C.C. and K.-F. Liu, 1987. A Bingham-Plastic model for a muddy seabed under long waves. *J. Geophys. Res.*, 92, 14581-14594

Son, M., and Hsu, T.-J., Flocculation model of cohesive sediment using variable fractal dimension, submitted.

Toorman, E. A., 1999. Sedimentation and self-weight consolidation: constitutive equations and numerical modeling, *Geotechnique*, 49(6), 709-726.

Trowbridge, J. H., and Kineke, G. C., 1994, Structure and dynamics of fluid mud on the Amazon continental shelf. *J. Geophys. Res.*, 99(C1), 865-874.

Traykovski, P., P. Wiberg, and W. R. Geyer, 2007. Observations and modeling of wave-supported sediment gravity flows on the Po prodelta and comparison to prior observations from the Eel shelf, *Cont. Shelf Res*., 27, 375-399.

Winterwerp, J.C., 1998. A Simple Model for Turbulence Induced Flocculation of Cohesive Sediment. *J. Hydraul. Res*. 36(3), 309-326.

PUBLICATIONS

- Hsu, T-J, Traykovski P. A., and Kineke, G. C., (2007) On modeling boundary layer and gravity driven fluid mud transport, *J. Geophys. Res.*, 112, C04011, doi:10.1029/2006JC003719 [PUBLISHED, REFERRED]
- Hsu, T-J, 2006. On modeling boundary layer and gravity driven fine sediment transport. *Proceedings 30th International Conference on Coastal Engineering*, [PUBLISHED]
- Sung, L.-P, Hsu, T.-J., and Traykovski, P. A., A fluid mud transport model and its application to wave-supported gravity-driven mudflows, *Eos Trans. AGU*, 87 (52) Fall Meet. Suppl., Abstract OS31A-1622, 2006. [PUBLISHED]
- Hsu, T.-J. and Son, M. A fine sediment transport modeling framework and its application to fluid mud processes, *Coastal Sediment '07*, ASCE, New Orleans. [PUBLISHED]
- Son, M., and Hsu, T.-J. Flocculation model of cohesive sediment using variable fractal dimension. [SUBMITTED]